MODULE-III:

FIBRE OPTICS

Introduction to Fibre Optics:

Fibre optics involves technology for transmission of information by guiding optical energy through hair thin fibres made of glass or transparent dielectric materials. So, optical fibers are thin, transparent and flexible strand that consists of a core surrounded by cladding.

The idea of using light waves for communication can be traced to as early as 1880 when Al. Graham Bell invented the photo phone in which speech was transmitted by modulating a light beam which travelled through air to receiver. Since optical beams have frequencies in the range of 10^{14}-10^{15}Hz, the use of such beams as the carrier would increase the information transmission capacity of the system compared to systems using radio (10^{6}Hz) or micro(10^{10}Hz) waves.

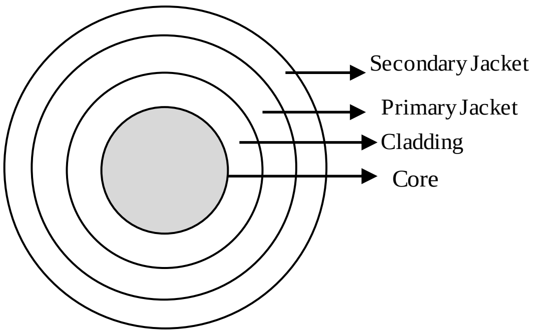
Structure of optical fibre:

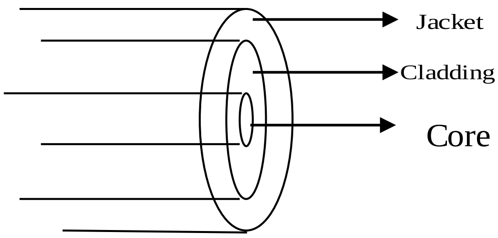
Most optical fibers are made up of glass. They are in general thinner than human hair and they have got three main parts.

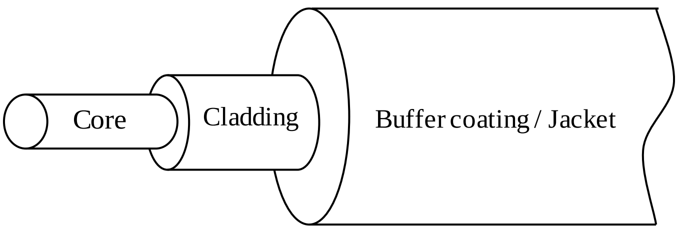
a. **The Core:** The cylindrical central part of the optical fiber is called as core. It is made up of pure silica. The diameter of the core is 1 μ m to100 μ m. The Refractive index of the core is higher than that of cladding.

b. **The Cladding:** The cylindrical coating over the core is called as cladding. It is made up of silica doped with suitable amount of Germanium and fluorine to control the refractive index. The diameter of the cladding is of the order of 100 μ m to 400 μ m. The refractive index of the cladding is less than the core so that the total internal reflection is possible.

c. **The Jacket:** The outermost coating is made up of polymeric material and is called the jacket. It protect core and cladding from external damages that might result from abrasion and external pressure. The thickness of the jacket is from 60 μ m to 250 μ m. Sometimes a secondary jacket of hard material covers the primary jacket for additional protection.

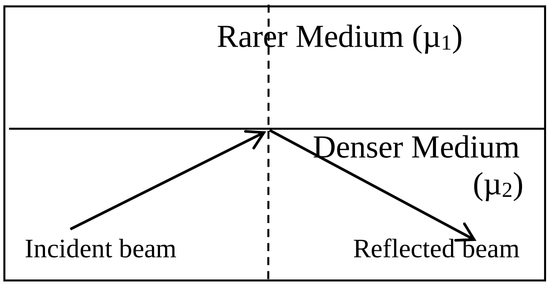






Principle of Light Propagation through Optical Fibre: (Total Internal Reflection)

The operation of simple optical fiber is based on the principle of Total Internal Reflection. In Total Internal Reflection, if light is refracting from denser to rarer medium and the angle of incidence is more than the critical angle, then there will be no refraction and the incident ray will be reflected back obeying the laws of reflection.



The light ray is incident on the core in such a way That after entering into the core, it strikes the core-cladding Boundary at an angle more than the corresponding critical angle producing Total Internal Reflection. The optical signal cannot escape through the core-cladding interface and are guided through the core of the fiber.

Characteristics of optical fibres:

- **a.** Optical fibers have greater capacity due to the larger band widths available with optical frequencies.
- **b.** Optical fibers are immune to static interference caused due to lightning and other external electrical noise sources. This is because optical fibers are non conductors of electricity.
- **c.** Optical fibers are immune to cross talk between cables caused by magnetic induction.
- **d.** Optical fibers have lower signal attenuation than other propagation systems.
- **e.** Due to substantially lighter weight and smaller size, optical fibers require less storage space and are cheaper to transport.
- **f.** Optical fibers are more resistive to environmental extremes and corrosive liquids and gases.
- **g.** The cost of optical fibers is less as compared to metallic counterparts.
- **h.** The raw materials required for manufacturing optical fibers are cheap and plentily available.
- **i.** Optical fibers are more secured and impossible to tap to get the information without the knowledge of the user.
- **j.** The dielectric nature of optical fibers eliminates the spark and short circuit hazards.

Losses in Optical Fibers:

Every transmission line introduces some loss of power which is called as attenuation. Therefore, the power coming out of the fibre is less than the power entering into it. When light is coupled to an optical fibre for the purpose of communication, the reason for attenuation inside the optical fibres are bending, scattering and absorption.

i) Bending loss: It is of two types; one is macro bending loss caused by the curvature of the entire fibre axis and the other is the micro bending loss caused by micro deformations of the fibre axis.

ii) Scattering loss: A beam propagating at the critical angle or less will change direction after it meets the obstacle which means it is scattered. This scattering effect prevents the attainment of total internal reflection at the core-cladding boundary. This results in a power loss because some light will pass out of the core.

iii) Absorption loss: We know that, if an incident photon is of frequency such that its energy is equal to the energy gap between two energy levels, then the photon will be absorbed. Similarly when light travels down an optical fibre encounters a material whose energy gap between two levels is exactly equal to the energy of these photons, then it leads to light absorption. This results in a loss of power of light travelling through the optical fiber. This loss depends upon the wavelength of light.

Attenuation in optical fibre

The light signal, as it travels through the fibre gets attenuated within the fibre due to the inherent properties of the material of the fibre. The sources of attenuation are:

- **a.** Energy absorption by lattice vibrations of the ions of the glass material.
- **b.** Energy absorption by impurities in the glass. The impurities are mainly hydroxyl ions which get introduced during fibre production at high temperature.
- **c.** Scattering of light due to local variations arise due to disordered structure of the glass.

All the above processes are wavelength dependent. By choosing a proper wavelength of the light signal where the absorption and scattering is minimum due to above processes, attenuation may be minimized. The best suited wavelengths for SiO_2-GeO_2 glasses are 1310nm and 1550nm.

Advantages of optical fiber

- **a.** Low attenuation.
- **b.** Smaller size and lighter weight.
- **c.** Electromagnetic isolation (Not vulnerable to interference, impulse noise, crosstalk).
- **d.** No electrical connection.
- **e.** Highly reliable.
- **f.** More secure.
- **g.** Greater bandwidth.
- **h.** Higher data rate.
- **i.** Lower cost per channel.
- **j.** Raw material plentily available.
- **k.** Higher information carrying capacity**.**
- **l.** High speed transmission.

Disadvantages of optical fibre

- **a.** Very difficult to couple.
- **b.** Sophisticated tools required for cabling purposes.
- **c.** Highly trained workforce required for installation.
- **d.** Complex testing methods. **e.** Ordinary source cannot be used

Light sources to be used in Optical Fibers:

Characteristics of Light sources to be used in optical fibre are,

- **a.** Monochromatic.
- **b.** Sufficiently intense (so that BER-Bit Error Rate,the fraction of bits transmitted that are received incorrectly can be met.).
- **c.** Capable of easily modulated with the signal.
- **d.** Small and compact.
- **e.** Durable or long lasting.
- **f.** Efficient in coupling to the optical fibre.
- **g.** Have sufficient linearity to prevent the generation of distortion.
- **h.** Mostly LED and Laser diodes are preferred to be used as source for optical fibre system.

Numerical Aperture of an optical fiber:

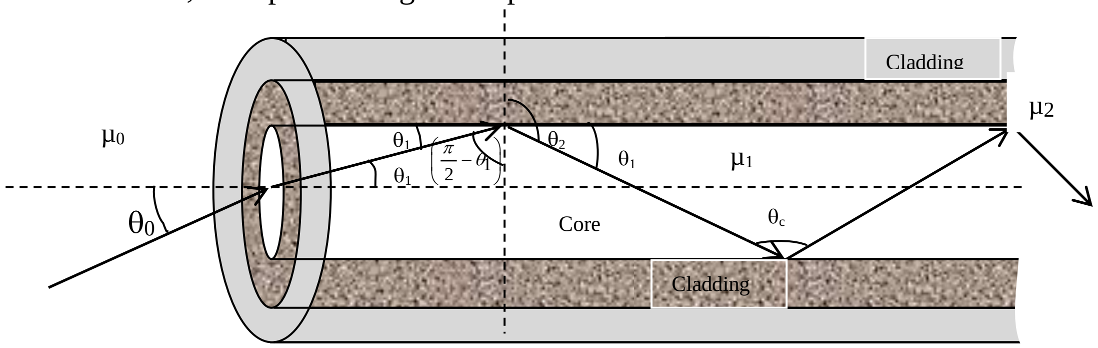
Numerical Aperture is a measure of the ability of an optical fiber to preserve and continue propagation of optical signals within the core of the fiber. Only those light rays those strike the core-cladding interface at an angle more than the critical angle can undergo Total Internal Reflection. The NA vary between 0.05 and 0.4.

The Numerical Aperture of an optical fiber is defined by,

$$\boxed{NA = \mu_0 \sin\theta_0} \qquad (1)$$

Where, μ_0= Refractive Index of the medium in which the fiber is immersed. Generally, it is air.

θ_0 = Angle of Incidence made by the light on the face of the optical fiber with the axis and is called as, Acceptance Angle for optical fibre.



[Light Propagation through Optical Fiber]

Let the ray of light be incident on the fibre face at an angle θ_0 with the axis of fibre. The angle of refraction be θ_1. The refracted ray faces the core-cladding interface at an angle $\theta_2 = (90 - \theta_1)$. As refractive index of core material μ_1 is greater than refractive index of cladding μ_2, total internal reflection takes place at core-cladding interface if $\theta_2 \geq \theta_c$, where θ_c is the critical angle.

If, $\theta_2 < \theta_c$, the light ray will be lost by refraction and when $\theta_2 \geq \theta_c$, it goes back to the core. Same way it suffers internal reflection at the core-cladding interface on the opposite side. Thus the ray undergoes multiple reflections and is guided through the fibre till it emerges at the other side. The operational condition for optical fibre is $\theta_2 \geq \theta_c$.

Applying Snell's law to the cross-sectional area, we can write,

$$\frac{\sin\theta_0}{\sin\theta_1} = \frac{\mu_1}{\mu_0}$$

$$\Rightarrow \boxed{\mu_1 \sin\theta_1 = \mu_0 \sin\theta_0} \qquad (2)$$

Similarly, applying Snell's law to the core-cladding surface, we can write,

$$\frac{\sin\left(\frac{\pi}{2} - \theta_1\right)}{\sin\theta_2} = \frac{\mu_2}{\mu_1}$$

$$\Rightarrow \boxed{\mu_1 \cos\theta_1 = \mu_2 \sin\theta_2} \qquad (3)$$

Squaring and adding equations (2) and (3), we can write,

$$\mu_1^2 \sin^2\theta_1 + \mu_1^2 \cos^2\theta_1 = \mu_0^2 \sin^2\theta_0 + \mu_2^2 \sin^2\theta_2$$

$$\Rightarrow \mu_1^2 = (NA)^2 + \mu_2^2 \sin^2\theta_2$$

$$\Rightarrow (NA)^2 = \mu_1^2 - \mu_2^2 \sin^2\theta_2 \qquad (4)$$

For total internal reflection to occur, θ_2 should be at least 90^0 and hence equation (4) can be written as,

$$(NA)^2 = \mu_1^2 - \mu_2^2 \sin^2 90$$

$$\Rightarrow (NA)^2 = \mu_1^2 - \mu_2^2$$

$$\Rightarrow \boxed{NA = \left(\mu_1^2 - \mu_2^2\right)^{1/2}} \qquad (5)$$

Equation (5) represents the expression for numerical aperture for an optical fiber. Numerical Aperture characterizes the fiber's ability to gather light from a source. So for different applications we need optical fibre with different numerical apertures. The formula for numerical aperture says we can change its value by changing μ_1 or μ_2. But actually, their difference ($\Delta\mu = \mu_1 - \mu_2$) matters, not the values of μ_1 & μ_2.

Case-I – The Upper Limit:

For, $\theta_2 = 90^0$, $\sin\theta_2 = 1 \Rightarrow \mu_1^2 = \mu_2^2 + 1$ taking $NA = 1$

This is a theoretical finding.

Case-II – The Lower Limit:

For, $\theta_2 = 0^0$, $\sin\theta_2 = 0 \Rightarrow \mu_1 = \mu_2$ taking $NA = 1$

This indicates that there is no cladding and the ray travels along the axis with zero intensity.

Acceptance Angle:

It is the maximum angle of incidence beyond which if a ray enters into the optical fiber core will not be guided completely through the fiber and will be lost in between as these rays will not satisfy the condition for total internal reflection.

This angle is 11^0. This means light rays which will make angles less than 11^0 with the optical fiber axis can undergo total internal reflection.

Acceptance cone:

Acceptance cone is the cone in which the light incident at acceptance angle or less than that on the optical fiber face such that the light will propagate through the fiber after total internal reflection.

Light will be saved inside the fibre if it comes from a source bounded by this acceptance cone. This means if a ray is not within the acceptance cone then, it will be lost while traveling inside the fibre.

Critical Incident Angle:

The critical incident angle is the angle the beam makes with the line perpendicular to the Optical boundary between the core and the cladding.

Critical Propagation Angle:

The critical propagation angle is the angle the beam makes with the central line of the optical fibre.

Question: Why Total Internal Reflection is the necessary condition for propagation of light through the optical fiber?

Ans.: We know that the incident beam is divided into two parts that is, reflected beam which will be saved and refracted beam which will be lost. When a beam strikes the core–cladding interface millions and millions of times while traveling through the fibre; therefore, if even a microscopic portion of the beam will be lost every time it hits this boundary because of refraction, the beam will be completely lost after traveling only a short distance. Thus, total internal reflection is the condition necessary for using

optical fibre for the purpose of communication and critical angle is required to achieve this condition. So to save light inside an optical fibre, it is necessary to direct rays at this critical angle.

Classification of optical fibres

The optical fibers can be broadly classified into two categories. One on the basis of refractive index variation along the core and the other is on the basis of mode of propagation.

A. Classification on the basis of mode of propagation:

The light can propagate inside an fibre only as a set of separate beams, or rays. These beams travel at different propagating angles and are called as modes. The number of modes that can be carried in an optical fibre is directly proportional to fibre diameter, numerical aperture and is inversely proportional to wavelength of light used. Depending on modes, optical fibres are divided into two types.

a. Single mode / unimode / Monomode fibre:

An optical fibre that supports only one fundamental mode is called as single mode or unimode or mono-mode fibre. It is a single strand of glass fiber with a typical core diameter of 2 to 10μm.

Advantages of Single mode / unimode / Monomode fibre:

i. It can carry higher band width.

ii. It gives a higher transmission rate.

iii. It provides least signal attenuation.

Disadvantages of Single mode / unimode / Monomode fibre:

i. Use of thin cores creates mechanical difficulties in the manufacture, handling, & splicing the fibres. So, it becomes very expensive.

ii. It requires a light source with narrow spectral width.

b. Multimode fibre:

A fibre that allows more than one mode to propagate inside it is called as multimode optical fibre. It can carry hundreds of modes. It is a multi strand of glass fibers with a typical core diameter of 50μm to 200μm. The most common size is 62.5μm.

Advantages of Multimode fibre:

i. It gives high bandwidth at high speeds over medium distances.

ii. It is more cost effective than single mode fibers.

iii. The light source can be of any spectral width.

Disadvantages of Multimode fibre:

i. In long cables, multiple paths of light can cause signal distortion at the receiving end.

B. Classification on the basis of Refractive Index variation:

Depending on the basis of refractive index variation along the diameter of the core of the optical fibre, there are two types of optical fibers.

a. Step Index Fibre (SIN):

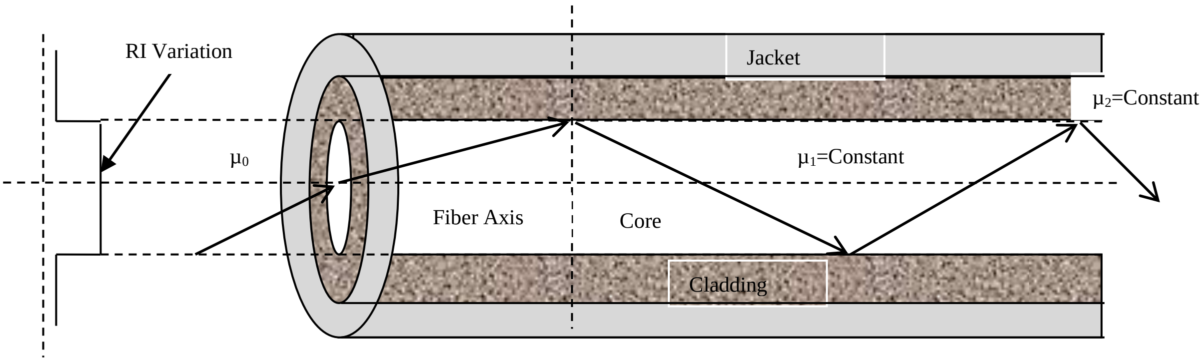


Figure showing refractive index variation in step index optical fiber and Monomode propagation of light through the core of the optical fiber

In this type of optical fibres, the refractive index of the core (μ_1) remains constant along the diameter throughout the core and also the refractive index of cladding (μ_2) remains same.

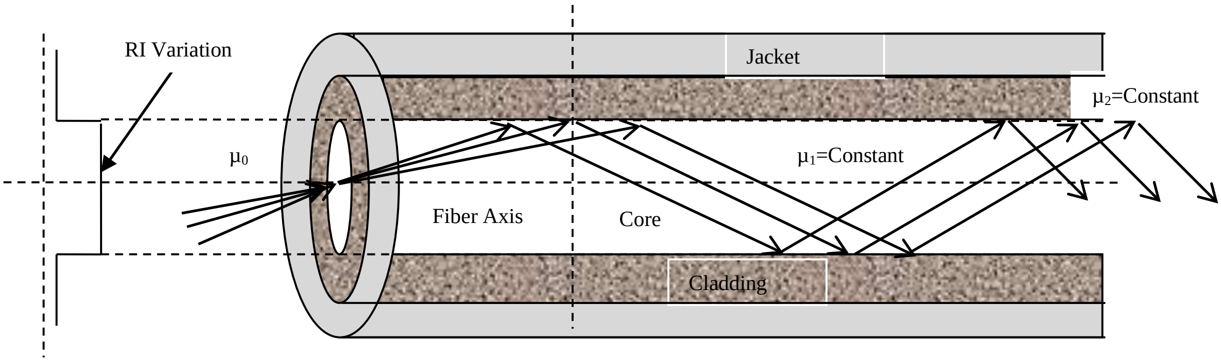


Figure showing refractive index variation in step index optical fiber and Multimode propagation of light through the core of the optical fiber

In step index multimode propagation, the light rays reach the other end of the fiber in different times. So, there is a distortion in the output.

b. Graded Index Fibre (GRIN):

In this kind of fiber, refractive index of cladding is uniform but the refractive index of core varies parabolically with respect to the core. It is maximum along the axis and gradually decreases towards the core-cladding interface. The speed of light is maximum near the surface and minimum along the axis.

The variation of refractive index is so accurate that all the light rays entering into the core arrive at the other end in same time minimizing the distortion.

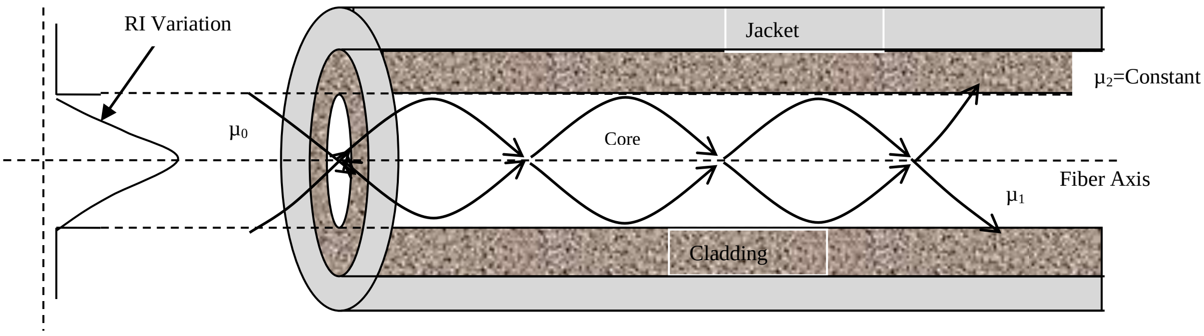


Figure showing refractive index variation in Graded index optical fiber and Monomode propagation of light through the core of the optical fiber.

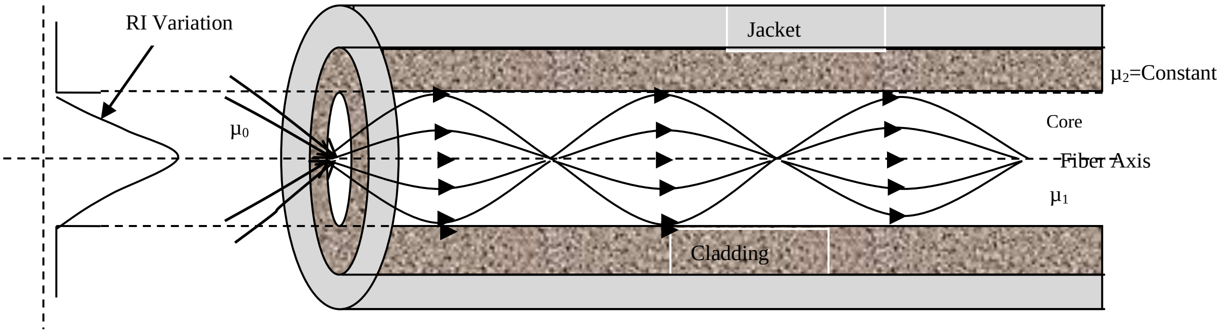


Figure showing refractive index variation in Graded index optical fiber and Multimode propagation of light through the core of the optical fiber

Comparison between step index fiber (SIN) and graded index fibre (GRIN)

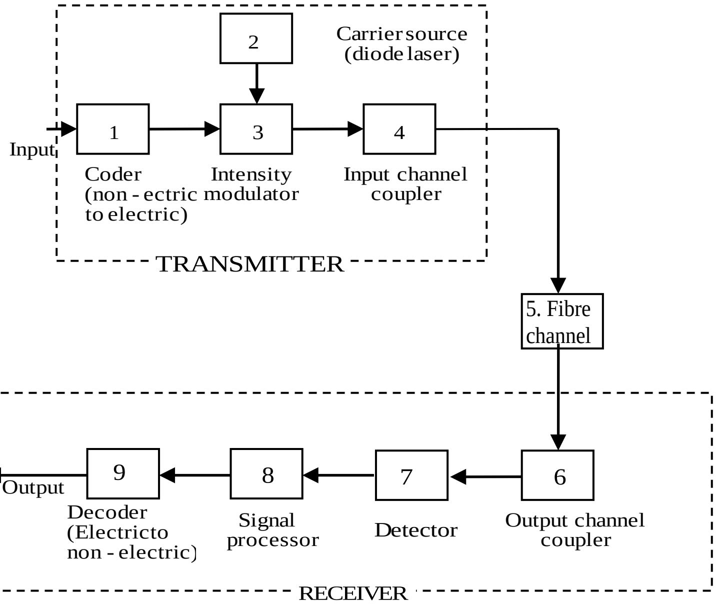
- **a.** Bandwidth: More in GRIN (600MHz) than in SIN(~50MHz).
- **b.** Attenuation: Generally, less in GRIN than in SIN.
- **c.** Mode dispersion: GRIN has inherent advantage in mode dispersion over SIN.
- **d.** Numerical aperture: For a given fibre diameter GRIN has smaller NA than SI.

Optical Fiber Communication System (FOCS):

The Fiber Optics Communication System (FOCS) are Fiber Optics Communication Link (FOCL), and Fiber Optics Transmission System (FOTS). The basic components of FOCS are,

- **a.** Optical transmitter.
- **b.** Fibres (channel or medium).
- **c.** Optical receiver

Fiber Optics Communication Link (FOCL):



Block Diagram of a FOCL

Transmitter:

a. **Coder:** It converts non electrical signal like sound or picture into electrical signal.

b. **Optical Source:** Light produced by it provides carrier wave.

c. **Modulator:** Intensity of the carrier wave is modulated in modulator and digitized, if required.

d. **Input Coupler:** Modulated output is connected to the fibre by the input coupler.

Receiver:

a. **Output Coupler:** Fibre channel is coupled to photo detector by output coupler.

b. **Photo Detector:** It converts the output into electrical form. In this stage, output gets demodulated and separated from carrier wave.

c. **Signal Processor:** Signal is amplified and made free from undesirable parts.

d. **Decoder:** Electric signal is finally converted into none-electrical signal to get the message in the decoder. The optical fibre channel is coupled to the photo detector by output coupler.

Advantages of FOCL:

i. Due to small size and mass, FOCL has got distinct advantages over conventional wired line.

ii. Because of plentily availability of optical fiber raw materials, the cost is very low.

iii. Due to wide range of frequency, FOCL can handle 10^{10} calls or 10^{6} TV programs by wavelength division multiplexing (WDM).

iv. With introduction of very recent developments in fiber communication, the losses can be compensated and the shape and width of calls can be maintained for long distance without using repeaters.

v. The noise immunity to external electromagnetic influences is very high.
vi. No adjacent line interference.
vii. Privacy of information exchange is ensured and hence it is suitable for Defence Communication Link (DCL)
viii. The working of FOCL is not affected even at high temperature.
ix. There is no requirement of protection from voltage fluctuations and earthing.
x. FOCL can be used in areas where isolation from electrical installation is a problem.

Disadvantages of FOCL:

i. Overhead FOCL is not feasible.
ii. Underground laying of lines is relatively expensive.
iii. Any crack or bend in the fiber link will result in loss and distortion of a signal.
iv. Repairing of the broken link is not desirable and always needs replacement.

Applications of optical fibre

a. Optical fibers have got application in Information transmission fields such as, communications, cable T.V., Networking (LAN), Imaging, Monitoring power grid system.
b. In Medical field the optical fibers are used in dental surgery, endoscopy, general surgery.
c. Optical Fibres can be used as couplers, sensors and switches.
d. Single mode fibre finds its use in undersea cable system for its larger bandwidth.
e. Graded index multimode fibre is used in Intra-city trunks between telephone central offices.
f. In data links, a step index multimode fibre is used, as lower bandwidth is required.
g. Optical fibers can be used in security fences where these fibers run along the metal strand of the fence. If the strand is cut at any point, the light beam is interrupted and an alarm sound.

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